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A comprehensive theoretical and experimental investigation was undertaken to study the effects of projectile impact on plates involving targets of soft aluminum and mild steel, with thicknesses ranging from 0.05 to 1 in. The preponderance of the tests and all analyses were concerned with normal impact; however, a substantial number of experiments involved oblique impact with angles up to 50°. Projectiles of ½-in. diameter consisted of hard-steel cylinders with masses of about 40 g, or of 16g soft aluminum cylinders. Strikers were fired

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pneumatically at velocities up to 600 ft/s, and with a powder gun up to 3000 ft/s at the Naval Weapons Center, China Lake, CA, where some metallurgical post-impact target examinations were also performed.

The test results correlated well with three different analytical predictions developed for the three nose shapes, respectively. A separate investigation of the influence of a predrilled hole in the target on central, normal impact of concial-nosed strikers evidenced a greater projectile energy loss than for an intact plate due to occurrence of extrusion rather than petalling for certain hole/projectile diameter ratios. Target deformation and fracture initiation was also extensively investigated experimentally just below and just above the ballistic limit.

FOREWORD

This document represents the Final Report of Contract Number DAA G-29-80-K-0052 with the U. S. Army Research Office, supervised by Principal Faculty Investigator Werner Goldsmith, Professor of Mechanical Engineering, University of California, Berkeley. Although the work was primarily executed on the campus of the University of California, a collaborative effort was undertaken with the Engineering Sciences Division, Code 383, Naval Weapons Center, China Lake, CA, 93555, whose assistance is gratefully acknowledged. In particular, this cooperative action permitted the investigation of projectile penetration at speeds attainable only by employment of a powder gun. Safety reasons precluded the use of such a device in the laboratories of the University. The personnel of the Naval Weapons Center also executed the metallurgical analysis of the targets after firing. An NWC Technical Report is currently nearly complete that details this phase of the investigation, conducted both at normal and oblique incidence.

The writer would also like to express his gratitude to numerous Visiting Scholars whose activities that extended far beyond their paid working hours, and is still continuing have helped enormously to secure important results and to ensure the success of the investigation. The project has also permitted the training of graduate students in the area of terminal ballistics, has exposed a number of undergraduate students to this area (at least two of these will continue this research at a graduate level leading to a higher degree), and has resulted in numerous publications either just in print, accepted or submitted to archive journals that, it is hoped, will provide useful information to the community and perhaps stimulate additional interest in this important area, where very little fundamental research is conducted in American universities.

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PROBLEM STATEMENT

A theoretical and experimental investigation was undertaken under ARO Contract No. DAA G-29-80-K-0052 to study penetration and perforation phenomena incident to the impact of projectiles on metallic plates. The targets consisted of 2024-0 aluminum or mild steel struck by projectiles composed of either hard steel or soft 2024-0 aluminum. All analyses and the majority of the tests were concerned with normal impact, but a substantial number of experiments were conducted at angles of obliquity up to 50^o. Hard-steel strikers were in the form of ½-in. diameter cylinders with either blunt, hemispherical or conical nose shapes, with masses of about 40g, or, in a few instances, were spherical in shape. Only blunt-nosed soft aluminum cylinders were employed as strikers. Plate thicknesses ranged from 0.05 in to one in, and projectile velocities were varied from about 60 ft/s to 3300 ft/s.

Several special series of experiments were conducted. These include the determination of the effect of coating cylindro-conical steel projectiles with Teflon in order to determine the effect of such a procedure on the penetrability of metallic plates. Another group of tests was concerned with the results of superposing various nose radii on a 60^o cylindro-conical hard-steel projectiles relative to their perforation efficiency. Finally, an extensive investigation was executed on relatively thin plates composed of soft aluminum and mild steel to determine the features of the normal impact of cylindro-conical and blunt hard-steel strikers just below and just above the ballistic limit.

The objective of the experiments was to serve as a guide for the construction of phenomenological models of the penetration and perforation processes and, further, to provide experimental data for comparison with the predictions of such analyses. This permitted an evaluation of the efficacy of the theories and indicate regions where further investigations should be conducted. Although many numerical solutions have been developed for oblique impact on targets, only one phenomenological approach involving a spherical striker has been disseminated recently on an unclassified basis (1). The vast collection of information on oblique impact developed here and similar data of the events occurring near the ballistic limit should serve as a basis for the development of additional models designed to portray these impact situations. Substantial development of a variety of instrumentation procedures were required to permit the measurement of initial and terminal projectile (and plug, when extant) velocities and of the force and deformation histories of the targets.

SUMMARY OF RESULTS

Three separate analytical approaches were developed to describe the impact at normal incidence of cylindrical strikers with blunt, conical and hemispherical nose shapes, respectively, on metallic plates thin and of moderate thickness. The first of these involves either a rigid or a deformable striker and a target whose mechanical behavior in both compression and shear can be represented by a strain-rate independent rigid/plastic constitutive relation. Transient plastic waves are utilized to delineate a five-stage perforation process consisting sequentially of indentation, plug formation, separation and slipping, and of post-perforation deformation. The dynamic target response is included in the model by the action of a propagating plastic hinge resulting from the shear applied at the projectile periphery. Equations of motion are obtained for the limited number of units defined by the system components, the wave fronts and the hinges. The numerical results obtained from a digital computer are in excellent correspondence both with the data obtained from concurrent tests and with tnat obtainred by other investigators. The axial shear deformation mode does not predict the total target deflection and contributes only within a narrow region beyond the projectile radius; inclusion of the more dominant effect of bending near the ballistic limit would further improve the correlation. At impact velocities substantially beyond the ballistic limit, the effect of the target response is small.

The normal impact of a cylindro-conical projectile on a metallic target was analyzed by means of an energy balance. Since petalling always occurs under these conditions, this balance included the phenomena of crack propagation, plastic hinge motion following crack arrest that results in petal bending, and further petal rotation un to and beyond the passage of the projectile, as well as bending deformation of the plate based on a previous investigation and relying to some extent upon empirical data (2). Predictions of the final projectile velocity were in excellent agreement with test results except in the immediate vicinity of the ballistic limit.

The above analysis was extended to include the case when this projectile impinged centrally and normally on a predrilled hole in the target with a radius less than that of the projectile. This results in an energy loss greater than that for an intact plate due to the partial or total metamorphosis of the petalling process into extrusion, which requires more energy. The theoretical treatment did not include the dishing energy, as for the case of the intact plate, because insufficient information is currently available for the bending process in a preperforated plate. In consequence, only qualitative comparisons could be executed with corresponding experimental results, but the trend under both circumstances is the same.

The impact and perforation at normal incidence of spheres and hemispherically-tipped strikers was portrayed by an extremely simple model involving equivalent masses of the plate and plug, and either one or two linear viscous resistances, respectively. The parameters of the system occurring in the theory could be completely determined from an energy balance for plate and projectile and an assumed plate deformation shape ascertained from a previous investigation (2). A closed-form solution was obtained by use of the same techniques for deriving the system parameters in the non-perforation case for the situation when perforaton occurs; this, however, also required the specification of suitable initial conditions representing the initiation of plug motion. This analysis provided predictions found to be in excellent agreement below and in satisfactory agreement above the ballistic limit relative to measured peak force and deformation parameters, as well as terminal velocities. Clearly, such an analysis can be considered only as an interim description of the event that should be described by a continuum-mechanical representation. It is likely that the model utilized here is an approximation of a special case of such a more exhaustive theoretical construction.

At velocities high relative to the ballistic limit, the effect of the nose shape is expected to be minimal; this has been borne out by experiments.

Several novel techniques of measurement were developed during the course of the investigation. The first of these consisted of two designs for a force transducer embedded in the projectile whose acceleration history was registered on an oscilloscope. The unit consists of an insulated quartz crystal that is backed by an inertial mass. The front side is connected to the projectile, while the insulated plate is connected to the oscilloscope input; the rear of the crystal is connected to the barrel which is grounded. Contact of the projectile with the plate produces the deceleration whose history is displayed and recorded on the oscilloscope.

Another unusual technique was represented by the determination of the final velocity of a projectile when preceded by a plug; this occurred in all perforation tests involving a blunt cylinder or sphere at normal incidence and many tests at obliquity, and in a few cases for the hemispherically-nosed bullet (which was fired only at normal incidence). The arrangement consisted of a laser beam directed across the bullet trajectory just beyond the target, a zig-zag laser net a further distance of about 20 cm downstream, a timer triggered by the interruption of the first laser beam and stopped by that of the second, and a digital storage oscilloscope. The latter, triggered by the stop signal of the counter, records the output of the photodiode receiving the light from the zig-zag beam that show the passage times of both plug and projectile relative to the counter stop signal. These data permit the evaluation of both plug and terminal projectile velocity.

A special strain gage consisting of a strip of elastomeric carbon was applied to the target with special tools. This material is capable of elongating up to 100% with a nonlinear change in resistivity which was obtained analytically. Wires soldered to this gage were attached to the input of an oscilloscope that recorded the change in resistance. Additionally, grid techniques were employed to measure both the radial and circumferential deformations and strains.

Extensive experimental investigations were conducted at normal incidence for all strikers previously cited; in part, this information was employed to check the accuracy of the theoretical predictions, in part additional test results were collected to indicate the trends in the variation of the mechanical parameters examined relative to impact velocity, projectile nose shape and target thickness. Particular attention was directed to the peak force on the striker generated, deformation of the target, radial and tangential strains, plug dimensions (when produced) or crack lengths, and terminal projectile velocities. The data were frequently represented in terms of projectile momentum and/or energy. As stated, excellent correspondence was noted between analytical predictions and test data except in the immediate vicinity of the ballistic limit.

Cylindro-conical hard-steel projectiles coated with Teflon did not exhibit greater penetrability for metallic plates than comparable bullets without such a coating. Substantial national publicity concerning such an effect for lead bullets prompted an examination of this situation. It is concluded that the claimed enhanced perforation of body armor for coated bullets must be either due to the ability of the coating to retain the original shape of the lead projectile or else to some chemical/thermodynamic interaction of the coating with the body armor that significantly reduces the resistance to penetration.

An extensive investigation has been conducted to examine the processes involved in the perforation of plates by blunt and conical-nosed cylindrical projectiles at angles of incidence ranging from normal to 50°. For many projectile target combinations, the percentage velocity drop first decreases to a minimum as a function of increasing angle of incidence, and then rises up to the value of the ballistic limit. This behavior is similar to that previously documented for the perforation of metallic plates by spheres (3).

An examination of the behavior of thin, metallic plates struck at normal incidence by hard-steel blunt and cylindro-conical projectiles has been performed at speeds corresponding to those just below and just above the ballistic limit. The latter, defined here as the first indication of fracture on the distal side, was established as follows: (a) for a 2024-0 aluminum target, a value of 64 m/s was determined for a 1.27 mm plate, and values of 21.4, 57 and 128 m/s were found for a 60° conical-nosed projectile, respectively; a magnitude of 103 m/s was established for the blunt cylinder striking a 3.18 mm thick specimen. A limit of 23.1 m/s for a 1.18 mm thick plate and a value of 90.5 m/s for a 3.18 mm thick sample, both composed of mild steel, were evaluated for a 60° conical nose shape. (b) Blunt soft aluminum cylinders deformed substantially under similar normal impact conditions and concomitantly produced much smaller craters at corresponding velocities. All projectiles had a diameter of ½ in.

Speeds below the ballistic limit produce a dimple on the distal side of these plates, accompanied by a conical indentation for the cylindro-conical projectile. For such projectiles, the plate contour at initial perforation corresponds to an included angle approximately twice that of the 60° tip employed. A large number of small petals, of the order of 25-30, were generated on the impact side of the plate in most of the tests, representing the material displaced from the crater by compression. In a few tests involving impact on blocks of this soft aluminum and mild steel sufficiently thick so that no deformation occurred on the distal side, the blunt projectile produced a rise in the impact surface without generation of the small petals, whereas the cylindro-conical bullet did generate such petals.

Metallurgical examination of projectiles and targets employed in the oblique impact tests at speeds ranging from 1000-3000 ft/s have been conducted at the Naval Weapons Center, China Lake, CA.

PUBLICATIONS AND TECHNICAL REPORTS

a) In Print

1) "Constraint to Side Flow in Plates," by J. Liss, W. Goldsmith, and F. E. Hauser, J. of Applied Mechanics, v. 50, pp. 694-698, Sept. 1983.

2) "A Phenomenological Penetration Model of Plates," by J. Liss, W. Goldsmith, and J. M. Kelly, Int. J. of Impact Engineering, v. 1,

3) A Phenomenological Penetration Model of Thin Plates, by J. Liss. Ph. D. Dissertation, University of California, Berkeley, 1982.

b) Accepted for Publication

1) "Plate Perforation Phenomena due to Normal Impact by Blunt Cylinders," by J. Liss and W. Goldsmith, Int. J. of Impact Engineering, v. 2, March, 1984.

2) Discussion (invited) of "Calculation of Penetration" (by K. D. Kinsey), by W. Goldsmith, Proc. of the Workshop on the Theoretical Foundation for Large-Scale Computations of Nonlinear Material Behavior, Northwestern Univ. (Oct. 24-26, 1983).

3) "Petalling of Thin, Metallic Plates during Penetration by Cylindro-Conical Projectiles," by B. Landkof and W. Goldsmith, Int. J. Solids and Structures.

4) "Initiation of Perforation in Thin Plates by Projectiles," by W. Goldsmith (invited). Commemorative Volume on the Occasion of the 25th Anniversary of Int. J. Mechanical Sciences to honor Prof. William Johnson. Oxford, Pergamon Press, 1984.

5) Normal and Oblique Impact of Cylindro-conical and Cylindrical Projectiles on Metallic Plates, by W. Goldsmith and S. A. Finnegan. U.S. Naval Weapons Center, China Lake, Calif. NWC TP 6479, 1984.

c) Submitted in Archive Journals

1) "Normal Impact and Perforation of Thin Plates by Hemispherically-Tipped Projectiles. I: Analytical Considerations," by N. Levy and W. Goldsmith.

2) "Normal Impact and Perforation of Thin Plates by Hemispherically-Tipped Projectiles. II: Experiments," by N. Levy and W. Goldsmith.

SCIENTIFIC PERSONNEL

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Werner Goldsmith, Ph.D., Professor of Mechanical Engineering, Principal Faculty Investigator
Michael M. Carroll, Ph. D., Professor of Applied Mechanics, Principal Faculty Investigator (during sabbatical leave of W. Goldsmith)
Benjamin Landkof, Ph. D., Visiting Associate Research Engineer
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Dr. Landkof and Mr. Levy have contributed substantially to the project subsequent to their departure from the University of California, Berkeley, without remuneration.

Joshua Liss received the Ph. D. degree in 1982 for work performed under the auspices of the present contract. J. Dual will receive a Master of Engineering degree in 1984, using the research performed on this contract for his research project, entitled "Force Measurement during Oblique Penetration of Metallic Targets". Mr. Levy will be using his research as a portion of a doctoral dissertation from the Technion, Haifa, Israel, with additional analytical investigations to be performed, if other graduate study requirements can be met.

BIBLIOGRAPHY

(1) Backman, M. E., Finnegan, S. A., and Witham, K. G., "Dynamics of the Oblique Impact and Ricochet of Non-deforming Projectiles against Thin Plates," Recent Advances in Engineering Science, Proc. of the 14th Annual Meeting of the Society of Engineering Science. Bethlehem, Lehigh University Publication, pp. 9-20, 1977. See also Backman, M. E., and Finnegan, S.A., U.S. Naval Weapons Center, China Lake, California, NWC TP 5844, September, 1976.

(2) Calder, C. A., and Goldsmith, W. "Plastic Deformation and Perforation of Thin Plates Resulting from Projectile Impact," Int. J. Solids and Structures, v. 7, pp. 863-881, 1971.

(3) Goldsmith, W., and Finnegan, S. A., "Penetration and Perforation Processes in Metal Targets at and above Ballistic Velocities," Int. J. Mechanical Sciences, v. 13, pp. 843-866, 1971.